

DIRECTIONAL DEPENDENCE OF Λ CDM COSMOLOGICAL PARAMETERSM. AXELSSON¹, Y. FANTAYE¹, F. K. HANSEN¹, A. J. BANDAY², H. K. ERIKSEN¹, K. M. GORSKI^{3,4,5}*Draft version March 22, 2013*

ABSTRACT

We study the previously discovered hemispherical power asymmetry (Eriksen et al. 2004, Hansen et al. 2004, Hansen et al. 2009) with the WMAP 9-year data. We find that the asymmetry is statistically significant at the 3.2σ confidence level for $\ell = 2-600$, where the data is signal dominated, using the WMAP 9-year KQ85 mask. The preferred asymmetry direction is $(l, b) = (227, -27)$, 44° away from the Ecliptic South Pole. Individual asymmetry axes estimated from six independent multipole ranges are all consistent with this direction. This agreement across a wide range of scales argues against a statistical *a-posteriori* interpretation of the effect. We estimate cosmological parameters on different parts of the sky and show that the parameters A_s , n_s and Ω_b are the most sensitive to the asymmetrically distributed power asymmetry. In particular, for the two opposite hemispheres aligned with the preferred asymmetry axis, we find $n_s = 0.96 \pm 0.022$ and $n_s = 0.99 \pm 0.024$, respectively.

Subject headings: cosmic microwave background — cosmology: observations — methods: statistical

1. INTRODUCTION

Shortly after the release of the first-year WMAP data (Bennett et al. 2003), Eriksen et al. (2004) and Hansen et al. (2004) reported a detection of a hemispherical power asymmetry in the cosmic microwave background (CMB) on large angular scales, $\ell = 2-40$. The power in this multipole range was found to be significantly higher in the direction towards Galactic longitude and latitude $(l = 237^\circ, b = -20^\circ)$ than in the opposite direction. Due to computational limitations at the time, higher multipoles were not investigated. These findings were supported by numerous other studies, e.g., Park (2004); Hansen et al. (2009) and references therein. However, the significance of the results has often been called into question, in particular, due to the alleged *a-posteriori* nature of the statistics used. In particular, it is debated whether the statistic has been designed to focus on visually anomalous features revealed by an inspection of the data (e.g., Bennett et al. 2011).

The only rigorous way to contend with this assertion is by performing repeated experiments and analysing the resulting independent data sets that may provide additional information. For cosmological studies, this is in general difficult, given that there is only one available Universe. However, it is not impossible — the standard inflationary cosmological model assumes that the Universe is homogeneous and isotropic, and that the initial fluctuations have amplitudes that are Gaussian distributed, independent and with random phase. This implies that different physical scales should be statistically uncorrelated, and therefore the morphology of the largest scales should not have any predictive power over the mor-

phology of the smaller scales. For the power asymmetry, this suggests that there is a possibility to study effectively new data sets by considering angular scales that have not previously been studied.

This extension to smaller angular scales was first undertaken by Hansen et al. (2009), when analyzing the WMAP 5-year temperature data set. The asymmetry was then found to extend over the range $\ell = 2-600$ with a preferred direction $(l = 226^\circ, b = -17^\circ)$ for the higher multipoles, fully consistent with the direction for the lower multipoles found in the original 1-year WMAP analysis. Two approaches were used for the analysis: (1) a statistical model selection procedure taking into account the penalty for including 3 new parameters (amplitude and direction of asymmetry), which showed that indeed an asymmetric model was preferred; and (2) a simple test in which the preferred power asymmetry axis was estimated independently for six multipole bins of width $\Delta\ell = 100$. It was found that these directions, which should be statistically independent, were strongly aligned; none of the 10000 simulated isotropic CMB maps showed a similarly strong clustering of preferred directions. An alternative approach modeled the power asymmetry in terms of a dipolar modulation field, as suggested by Gordon et al. (2005). Hoftuft et al. (2009) found a 3.3σ detection using data smoothed to an angular resolution of 4.5° FWHM, with an axis in excellent agreement with previous results. These studies, covering very different angular scales than those used in the original analysis, argue against an *a-posteriori* interpretation of the effect.

In this Letter, we repeat the high- ℓ analysis due to Hansen et al. (2009) using the WMAP 9-year (hereafter WMAP9) data. However, the main goal is to estimate cosmological parameters in the two maximally asymmetric hemispheres, in order to assess their stability with respect to the power asymmetry (for a closely related theoretical study, see, e.g., Moss et al. (2011) and references therein). A similar analysis was performed in Hansen et al. (2004) using the WMAP first-year data, but only taking into account the asymmetry observed in

magnus.axelsson@astro.uio.no

y.t.fantaye@astro.uio.no

¹ Institute of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, N-0315 Oslo, Norway² Universite de Toulouse, UPS-OMP, IRAP, Toulouse, France³ Jet Propulsion Laboratory, M/S 169/327, 4800 Oak Grove Drive, Pasadena CA 91109⁴ Warsaw University Observatory, Aleje Ujazdowskie 4, 00-478 Warszawa, Poland⁵ California Institute of Technology, Pasadena CA 91125

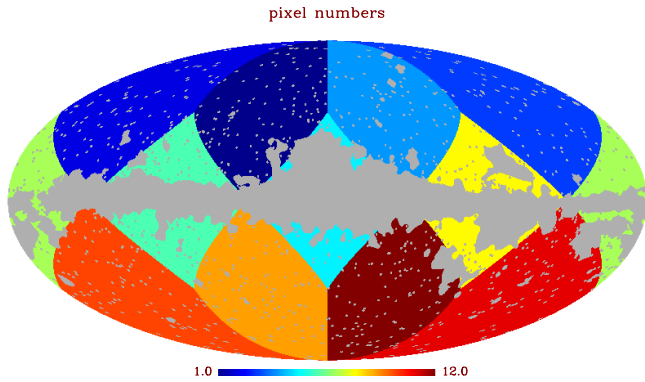


FIG. 1.— Regions used for parameter estimation.

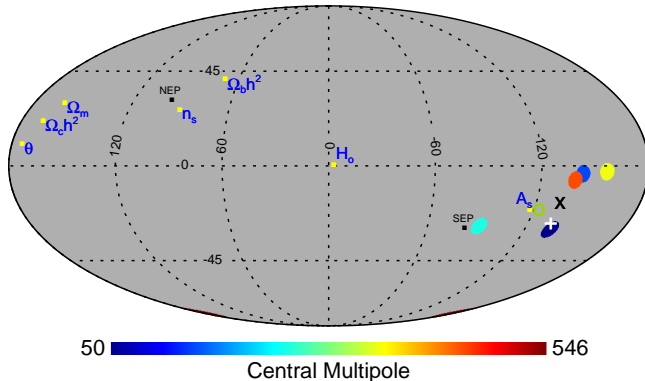


FIG. 2.— Dipole directions for six 100-multipole bins of the local power spectrum distribution derived from the WMAP9 combined V- and W-band map. We also show the direction for the full $\ell = 2 - 600$ range (white cross), for the $\ell = 2 - 40$ interval determined from the WMAP first year data (green circle) and the $\ell = 2 - 600$ range from WMAP5 (black cross). NEP and SEP denotes the North and South Ecliptic Poles. The dipole directions for the local parameter estimate maps are also shown.

the $\ell = 2 - 40$ range, limited by a grid-based approach, and consequently only considering a few cosmological parameters. In the following, we use CosmoMC to obtain the full posterior of all relevant cosmological parameters using the entire multipole range afforded by the WMAP9 data.

2. DATA AND METHOD

We use the publicly available WMAP9 temperature sky maps (Bennett et al. Bennett et al. (2012)), co-adding (with inverse-noise-variance weighting) the V (61 GHz) and W (94 GHz) band foreground-cleaned maps. We also generate a set of 10 000 simulated CMB-plus-noise Monte Carlo (MC) simulations based on the WMAP best-fit Λ CDM power spectrum Hinshaw et al. (2012), noise rms maps and beam profiles for the V and W bands. The WMAP9 KQ85 Galactic and point source mask is used to remove pixels with high foreground contamination.

Power asymmetry: — We estimate the C_ℓ auto power spectra locally on (1) regions corresponding to the twelve pixels of an $N_{\text{side}} = 1$ HEALPix map (always applying the Galactic and point source mask), illustrated in Figure 1; (2) on the two opposite hemispheres defined by

the direction of maximum asymmetry; (3) on disks of diameter 90 degrees centered on the directions of maximum asymmetry. The MASTER (Hivon et al. 2002) approach is used to estimate the power spectra. When applying the MASTER kernel to determine the pseudo-spectra, we bin the spectra into bins of width $\Delta\ell = 16$. We apply the same procedure to the set of 10 000 simulated maps.

To estimate the dipole directions of the local spectra, we combine the 16ℓ -bins further into blocks containing approximately 100 multipoles, following the binning used in Hansen et al. (2009). For each 100-multipole block determined at a given pixel, the mean power computed from the simulations is subtracted, and the results are divided by the similarly evaluated standard deviation in order to prevent the directions close to the Galaxy, where the Galactic mask increases the sample variance, dominating the fits due to possible large fluctuations.

In this way, we obtain an $N_{\text{side}} = 1$ map for each 100-multipole block as described above, and the value in each pixel shows the normalized deviation away from the best fit full-sky spectrum. We make a spherical harmonic transform of this map, and extract the dipole amplitude and asymmetry direction.

For an isotropic map, the power spectrum should be uncorrelated between multipoles. Although masking does introduce correlations between adjacent multipoles, it is not expected that this will be significant between the 100-multipole blocks, and therefore the dipole directions should be random. The degree of alignment between the dipole directions of different multipole blocks is then used as a measure of power spectrum asymmetry.

Cosmological parameter estimation: — Our primary interest here is to evaluate the directional dependence of the cosmological parameters in the temperature data. We apply a similar binning and power spectrum estimation method as described above. For the high- ℓ likelihood, we compute the MASTER estimates of the spectra from the full-resolution $N_{\text{side}} = 512$ map. For the low- ℓ likelihood, we replace the WMAP pixel likelihood by a MASTER estimate computed for a single bin, $\ell \in [2, 31]$. The maximum multipoles used in the parameter analysis are $\ell_{\text{max}} = 1008$ for the analysis on regions defined by the $N_{\text{side}} = 1$ pixels, and $\ell_{\text{max}} = 608$ for the hemispheres defined by the direction of maximum power asymmetry. For all spectra, we subtract the best-fit unresolved point source amplitude (Hinshaw et al. 2012) before parameter estimation.

Our TT likelihood code uses the offset log-normal term that was introduced into the WMAP likelihood in Verde et al. (2003) - hence the total likelihood is a linear combination of Gaussian and log-normal terms:

$$-\log \mathcal{L}(C_b | \hat{C}_b) \sim \frac{1}{3} \sum_{b,b'} \Delta C_b C_{bb'}^{-1} \Delta C_{b'}^T + \frac{2}{3} \sum_{b,b'} \Delta z_b \mathcal{Q}_{bb'}^{-1} \Delta z_{b'}^T \quad (1)$$

where \hat{C}_b and C_b are the estimated and model power spectra respectively, $\Delta C_b = C_b - \hat{C}_b$, $C_{bb'}^{-1}$ is the covariance matrix, estimated using CMB plus noise MC simulations, $z_b = \ln(C_b + N_b)$, (where N_b is the noise spectrum) and $\mathcal{Q}_{bb'} = (\hat{C}_b + N_b) C_{bb'}^{-1} (\hat{C}_{b'} + N_{b'})$ is the local transformation of the covariance matrix to the log-normal variables z_b .

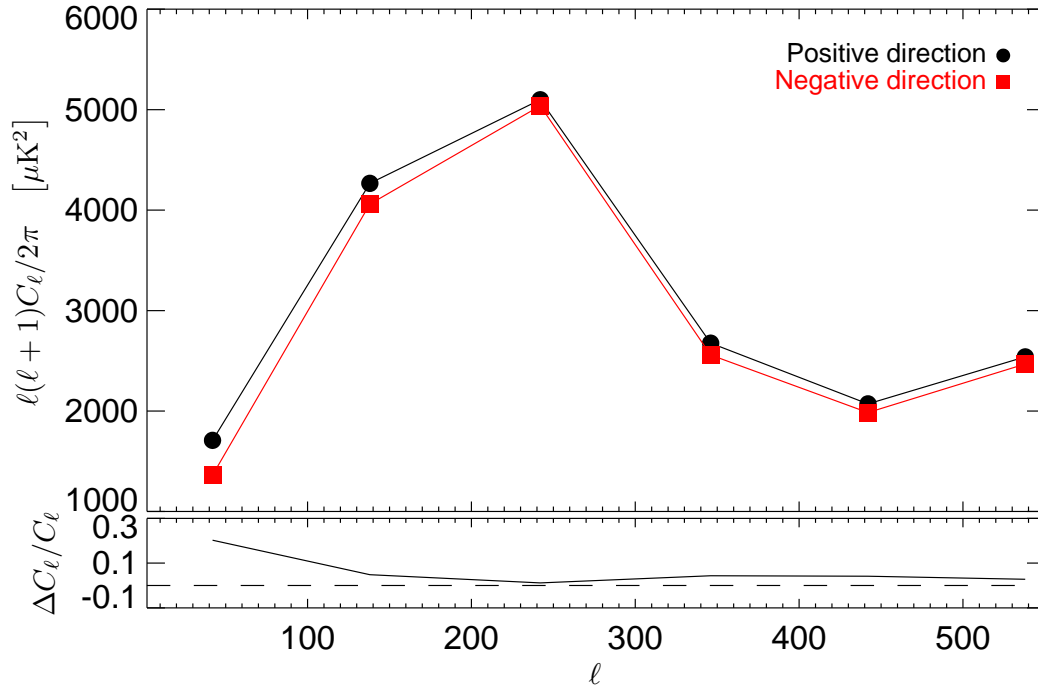


FIG. 3.— *Upper*: Power spectra estimated from two hemispheres defined by the preferred dipole direction determined from the $\ell = 2 - 600$ range, as computed within disks of diameter 90° . *Lower*: Difference between the two power spectra.

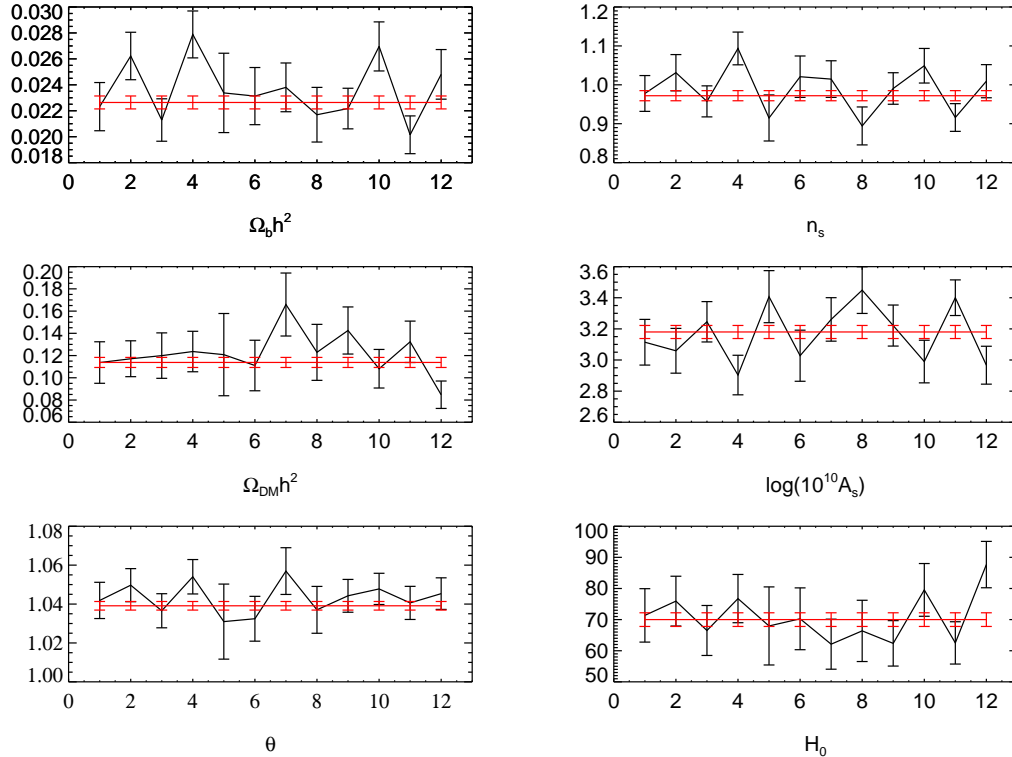


FIG. 4.— Estimated Λ CDM parameters: in red the WMAP9 full sky estimates, and in black estimates within regions defined by an $N_{\text{side}} = 1$ map. The values on the x -axes correspond to pixel number on the map. The estimates are based on multipoles in the range $\ell = 2 - 1008$.

To construct the covariance matrix, we use 500 CMB plus noise Gaussian simulations. The covariance matrix propagates the uncertainties introduced by effects such as the noise, mask geometry, and associated sample variance. We make no attempt to include beam uncertainty

in our pipeline.

The fractional areas of the 12 $N_{\text{side}} = 1$ patches range from $f_{\text{sky}} = 0.019$ in the Galactic center to $f_{\text{sky}} = 0.085$ in regions at high latitude. With such small patches, one might be concerned about the correctness of our likeli-

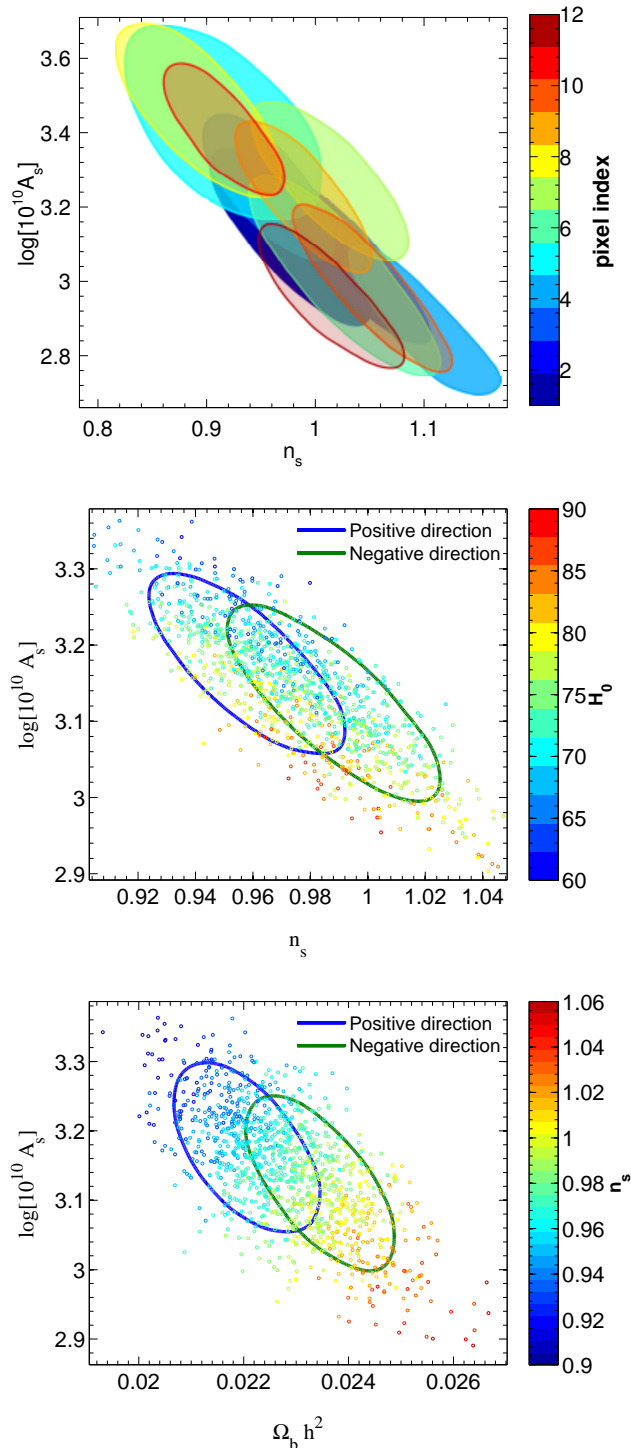


FIG. 5.— *Top*: Summary of n_s – $\log(10^{10} A_s)$ posterior in terms of 1σ contours for the 12 regions. *Middle*: The same, but evaluated from two opposite hemispheres aligned with the preferred asymmetry direction. Colored dots indicate the values of H_0 . *Bottom*: Same as the middle plot, but for $\Omega_b h^2$ – $\log(10^{10} A_s)$.

hood approximation. We have confirmed that the parameter estimates are unbiased, performing parameter estimation on some of the small regions in 500 simulated maps with known input parameters.

The final posterior distribution is comprised of the product of the likelihood and an eventual prior distribu-

tion that describes our previous knowledge of the parameters. Since we do not consider polarization in our analysis, we adopt the WMAP9 estimate of $z_{\text{rei}} = 10.6 \pm 1.1$ as a Gaussian prior on the re-ionization redshift.

3. RESULTS

In Figure 2, we show the first six dipole directions of the local power spectra as estimated on 12 pixels in 100-multipole bands, together with the dipole for the total multipole range $\ell = 2 - 600$. These directions are consistent with those found from the WMAP 1-year (Hansen et al. 2004) and WMAP 5-year (Hansen et al. 2009) data sets, which are also indicated in the figure.

For a statistically isotropic CMB temperature distribution, the dipole directions from uncorrelated power spectrum estimates should be distributed randomly on the sky. To quantify the significance of the power asymmetry, we consider the dispersion angle, which is defined as the mean angle, θ_{mean} , between all possible combinations of 100-multipole dipole directions up to a given ℓ_{max} . The expected dispersion angle for Gaussian simulations is 90 degrees, as confirmed by simulations. We calculate $\theta_{\text{mean}}(\ell_{\text{max}} = 600)$ for the WMAP9 data and compare it to the distribution obtained from 10 000 CMB plus noise simulations. We found that only 27 of these exhibited a lower dispersion angle, implying a 3.2σ significance for the power asymmetry. This is lower than previously reported in Hansen et al. (2009), where none of the 10 000 simulations had a similarly large mean angle. However, there are several changes in this analysis; (1) the new 9-year Galactic and point source masks remove a larger fraction of the sky, thus increasing the scatter on the dipole directions due to increased sample variance; (2) larger disks are now used since the smaller disks from the 5-year analysis result in several patches near the Galactic centre with an extremely small sky fraction in combination with the new Galactic mask; and (3) 12 independent patches are now used instead of 3072 overlapping ones to speed-up the computations. It is also interesting to note that we have tried a number of permutations of the individual yearly sky maps and found variations depending on how many years are included, and which particular years are excluded. The results always remain highly significant, and the variations are found to be within the expected noise fluctuations as tested with simulations.

In Figure 3, we show the difference between the power spectra computed for disks of diameter 90° , the so-called positive one centered at $(l, b) = (226^\circ, -27^\circ)$, i.e., the dipole direction for the full $\ell = 2-600$ range, and its opposite (negative) disk. This plot visually illustrates the power asymmetry seen in the WMAP9 sky. Next we consider if this asymmetry in power is reflected in fits to the standard Λ CDM cosmological parameters.

Figure 4 shows the directional dependence of the six main Λ CDM parameters. The computed values and their standard deviations are shown in black, and the corresponding results from the WMAP9 analysis on the KQ85 sky coverage is shown in red. The numbers on the x-axis correspond to the $N_{\text{side}} = 1$ pixel numbers. Inspecting the plots carefully, one finds that the majority of parameter estimates fall within $\sim 1\sigma$ of the WMAP9 full sky value. In Figure 2, we also show the dipole directions of the $N_{\text{side}} = 1$ parameter maps. Clearly n_s , A_s and Ω_b seem to show a directional dependence similar to the

power spectrum asymmetry and these seem to be the parameters mostly affected by the asymmetry. In the left top panel of Figure 5, we demonstrate the $A_s - n_s$ correlation with 1σ contours for each region. All contours are consistent with each other at better than 2σ , but some directional dependence is visible.

We also estimated parameters using hemispheres corresponding to the preferred power asymmetry direction for $\ell = 2 - 600$. The first case we considered was restricted to $\ell_{\max} = 608$ to cover only that part of the spectrum which is highly signal dominated and where the asymmetry is prominent. The absence of high multipoles leads to large uncertainties in the parameters of interest and the asymmetry becomes less visible. We then repeat the analysis but with $\ell_{\max} = 1008$. In this case the error bars on the parameters are improved and the error ellipses for A_s vs $\Omega_b h^2$ and A_s vs n_s computed on the positive (power-enhanced) and negative (power-deficit) hemispheres show a slight shift, as shown in the bottom panels of Figure 5. The best-fit parameters for each hemisphere lie just at the border or the 1σ contours from the opposite hemisphere. The two maximally asymmetric hemispheres do not, therefore, indicate parameter values significantly different from the WMAP9 full-sky results. It is interesting to note that the power-deficit hemisphere prefers in general a higher H_0 . The marginalised value obtained for the scalar spectral index in the two hemispheres is $n_s = 0.959 \pm 0.0224$ and $n_s = 0.989 \pm 0.0238$ respectively (an $\approx 1.3\sigma$ difference). It is interesting to note that in one hemisphere, the spectral index is different from 1 at almost 2σ whereas in the other it is fully consistent with 1.

4. CONCLUSIONS

We measure a statistically significant power spectrum asymmetry in the WMAP9 temperature sky maps with 3.2σ significance as measured by the mean dispersion among the preferred directions derived from six (nearly) independent multipole ranges between $\ell = 2$ and 600, using the conservative mask adopted in the WMAP 9-year analysis. Only 27 out of 10 000 simulations show a similarly strong alignment. Conversely, the cosmological parameters do not show a strong asymmetry, although the parameters A_s , n_s and Ω_b do indicate some sensitivity to the hemispherical power asymmetry. The average preferred direction points toward Galactic coordinates $(l, b) = (226, -27)$, or Ecliptic coordinates of $(l, b) = (81, -46)$, i.e., 44° away from the South Ecliptic Pole. Thus, contrary to a common misconception, the CMB power asymmetry axis is not strongly aligned with the Ecliptic plane.

FKH acknowledges OYI grant from the Norwegian research council. HKE acknowledges supported through the ERC Starting Grant StG2010-257080. We acknowledge the use of resources from the Norwegian national super computing facilities NOTUR. Maps and results have been derived using the HEALpix (<http://healpix.jpl.nasa.gov>) software package developed by Górski et al. (2005). Results have been derived using the CosmoMC code from Lewis & Bridle (2002). We acknowledge the use of the LAMBDA archive (Legacy Archive for Microwave Background Data Analysis). Support for LAMBDA is provided by the NASA office for Space Science.

REFERENCES

- Bennett, C. L., et al. 2003, *ApJS*, 148, 1
 —. 2011, *ApJS*, 192, 17
 Bennett, C. L., et al. 2012, *arXiv:1212.5225*
 Eriksen, H. K., Hansen, F. K., Banday, A. J., Gorski, K. M., & Lilje, P. B. 2004, *ApJ*, 605, 14
 Gordon, C., Hu, W., Huterer, D., & Crawford, T. 2005, *Phys. Rev. D*, 72, 103002
 Górski, K. M., Hivon, E., Banday, A. J., Wandelt, B. D., Hansen, F. K., Reinecke, M., & Bartelmann, M. 2005, *ApJ*, 699, 759
 Hansen, F. K., Balbi, A., Banday, A. J., & Górski, K. M. 2004, *MNRAS*, 354, 905
 Hansen, F. K., Banday, A. J., & Górski, K. M. 2004, *MNRAS*, 354, 641
 Hansen, F. K., Banday, A. J., Gorski, K. M., Eriksen, H. K., & Lilje, P. B. 2009, *ApJ*, 704, 1448
 Hinshaw, G., et al. 2012, *arXiv:1212.5226*
 Hivon, E., Górski, K. M., Netterfield, C. B., Crill, B. P., Prunet, S., & Hansen, F. 2002, *ApJ*, 567, 2
 Hoftuft, J., Eriksen, H. K., Banday, A. J., Gorski, K. M., Hansen, F. K., & Lilje, P. B. 2009, *ApJ*, 699, 985
 Lewis, A., & Bridle, S. 2002, *Phys. Rev. D*, 66, 103511
 Moss, A., Scott, D., Zibin, J. P., & Battye, R. 2011, *Phys. Rev. D*, 84, 023014
 Park, C. G. 2004, *MNRAS*, 349, 313
 Verde, L., et al. 2003, *ApJ*, 148, 195